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EFFECT OF MATERIAL PHASE CHANGE ON PENETRATION AND SHOCK WAVES

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This paper presents computed results that investigate the effect a material phase change has on penetration and shock waves. The effect of material strength is also presented for comparison. Three phase change conditions are used to investigate the phase change effect, and three levels of material strength are used to investigate the effect of strength. The results show that the shock wave response is very sensitive to the phase change condition and less sensitive to the strength. The penetration results show that the depth of penetration is very sensitive to the level of material strength and less sensitive to the phase change condition. The results also demonstrate that a phase change (resulting in a volume loss) produces a softer material response, which results in more penetration.

INTRODUCTION

Over the past several years there has been speculation that materials exhibiting a phase change may make effective armor material due to their ability to absorb energy [1-3]. It is difficult to determine experimentally the effect a phase change may have on ballistic performance because of the combined effects of strength, density, failure and Equation of State (EOS). This work uses computations to investigate the effect a phase change, and strength, have on ballistic performance (penetration depth) and shock wave response (wave profile). Three phase change conditions, and three levels of material strength are used. The effect of strength is included in this study to provide a relative comparison for the phase change effect. All phase change conditions considered herein result in a reduction in volume, as opposed to an increase in volume [3].

Recently, Johnson, Holmquist, and Beissel developed a new (JHB) computational constitutive model for brittle materials that allows for a phase change [4]. The JHB model has the ability to model the material with or without a phase change. If a phase change is included, the response can be modeled for various phase change pressures, the degree of phase change (amount of volume loss) and the degree of hysteresis. Hysteresis occurs when unloading does not return along the original loading path (no hysteresis), but instead, returns along a stiffer path resulting in a loss in volume. Figure 1 shows the pressure-volume portion of the JHB model for a material with no phase change, a material with a high (pressure) phase change, and a material with a low phase change. The high phase change response is for aluminum nitride.

COMPUTED RESULTS

The impact problems used for this study are presented in Figure 2. A tungsten projectile impacting an aluminum nitride target at 2000 m/s is used to investigate penetration and a (1D uniaxial strain) tungsten impactor striking an aluminum nitride target at 2000 m/s is used to investigate the shock response. The computations were performed with 1D and 2D Lagrangian finite elements [6], meshless particles (2D) [7, 8], and the JHB ceramic model [4].

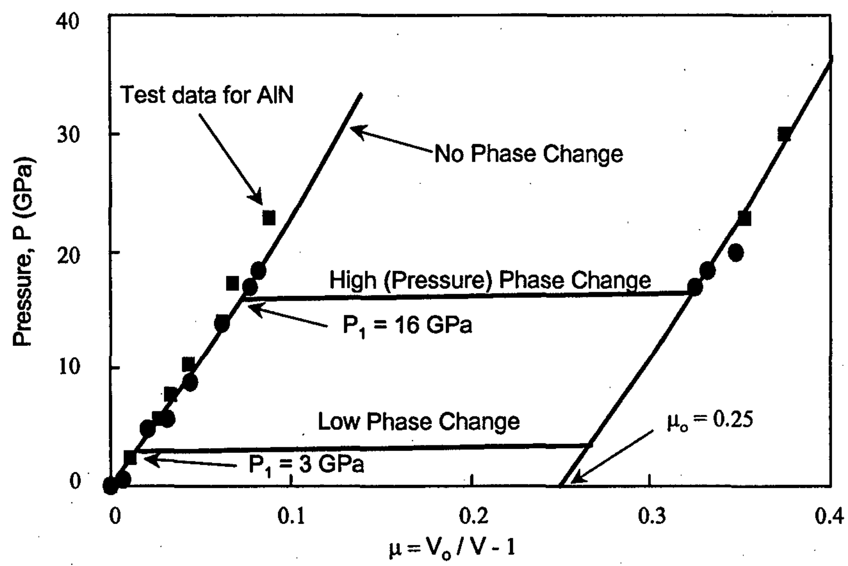

FIGURE 1. Pressure-volume response for a material with no phase change, a material with a high phase change and a material with a low phase change. The test data is for aluminum nitride, represented by the high phase change.

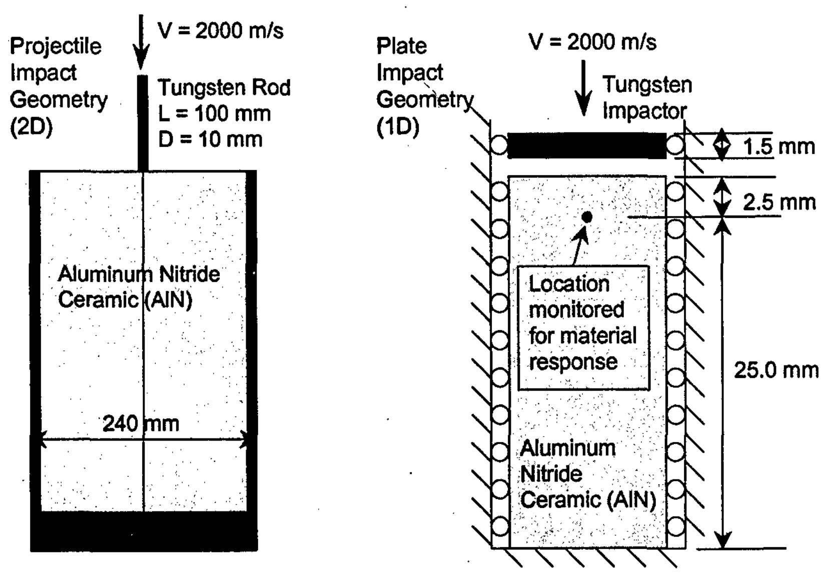

FIGURE 2. Initial geometry for the 2D projectile impact problems and for the 1D plate impact problems.

Effect of Phase Change and Strength on Penetration

Three phase change conditions are used to investigate the phase change effect, and three levels of material strength are used to investigate the effect of strength. In Figure 1 the no phase condition allows for no phase change, the high phase change condition (P1 = 16 GPa) represents the behavior of aluminum nitride [4], and the low phase change condition uses P1 = 3 GPa (to ensure that a substantial amount of target material experiences the phase change). The high strength condition uses a constant strength of 5 GPa, the no strength condition uses no strength (fluid behavior), and the strength with failure condition uses the response of aluminum nitride [4]. The high strength and no strength condition are used to decouple the phase change behavior from the strength and allow the effect of the phase change to be evaluated independently.

The computed results for the projectile impact problems are presented in Figures 3 and 4. The results indicate that a phase change softens the material response producing increased penetration. In Figure 4, when no strength is used, the penetration is much greater than the high strength condition and there is little effect from the phase change. The computed results are shown at 250 μs after projectile impact and the projectile is still penetrating at a high rate. When strength with failure (JHB model for AlN) is used the response is more complex. The results suggest that the high phase change condition produces a material response that is more resistant to penetration than with no phase change, although a closer investigation shows that this is not the case. When strength with failure is used the material strength goes from an intact state (approximately 5 GPa) to a failed state (approximately 0.2 GPa). The transition from the intact state to the failed state can be an unstable process. Small differences in the failure process can produce large differences in penetration because of the strong influence strength has on penetration. Figure 3 shows the final penetration depth as a function of the phase change pressure when strength with failure (JHB) is used. The penetration depths vary by +/- 15 % between phase change pressures of 20 GPa to 7 GPa. One would expect a gradual increase in penetration (from 131 mm) as the phase change pressure decreases. What happens here is that the softer response produced by the phase change is small relative to the penetration variability that occurs from the failure process. The softer response that occurs from the phase change is not large enough until pressures of about 6 GPa are reached. It is clear that the response is different for the low phase change condition. Because the material experiences substantial strain (for a small increase in pressure) as it goes through the phase change, the material damages more easily. This produces more material failure resulting in a deeper, more localized, penetration channel.

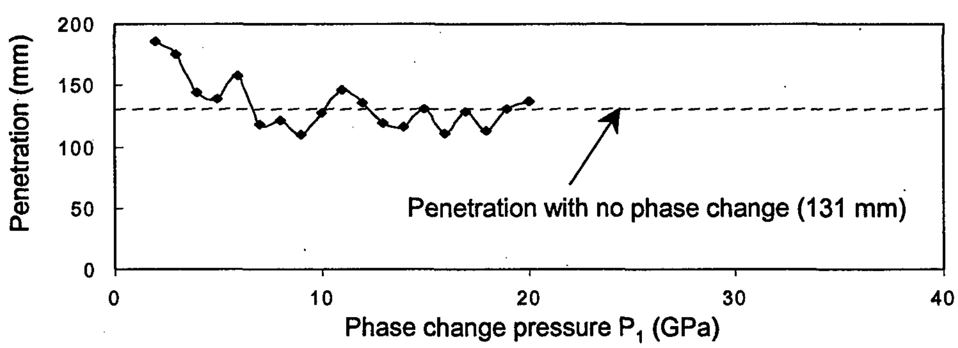

FIGURE 3. Penetration results using the JHB model for AlN, and various levels of the phase change pressure (P1).

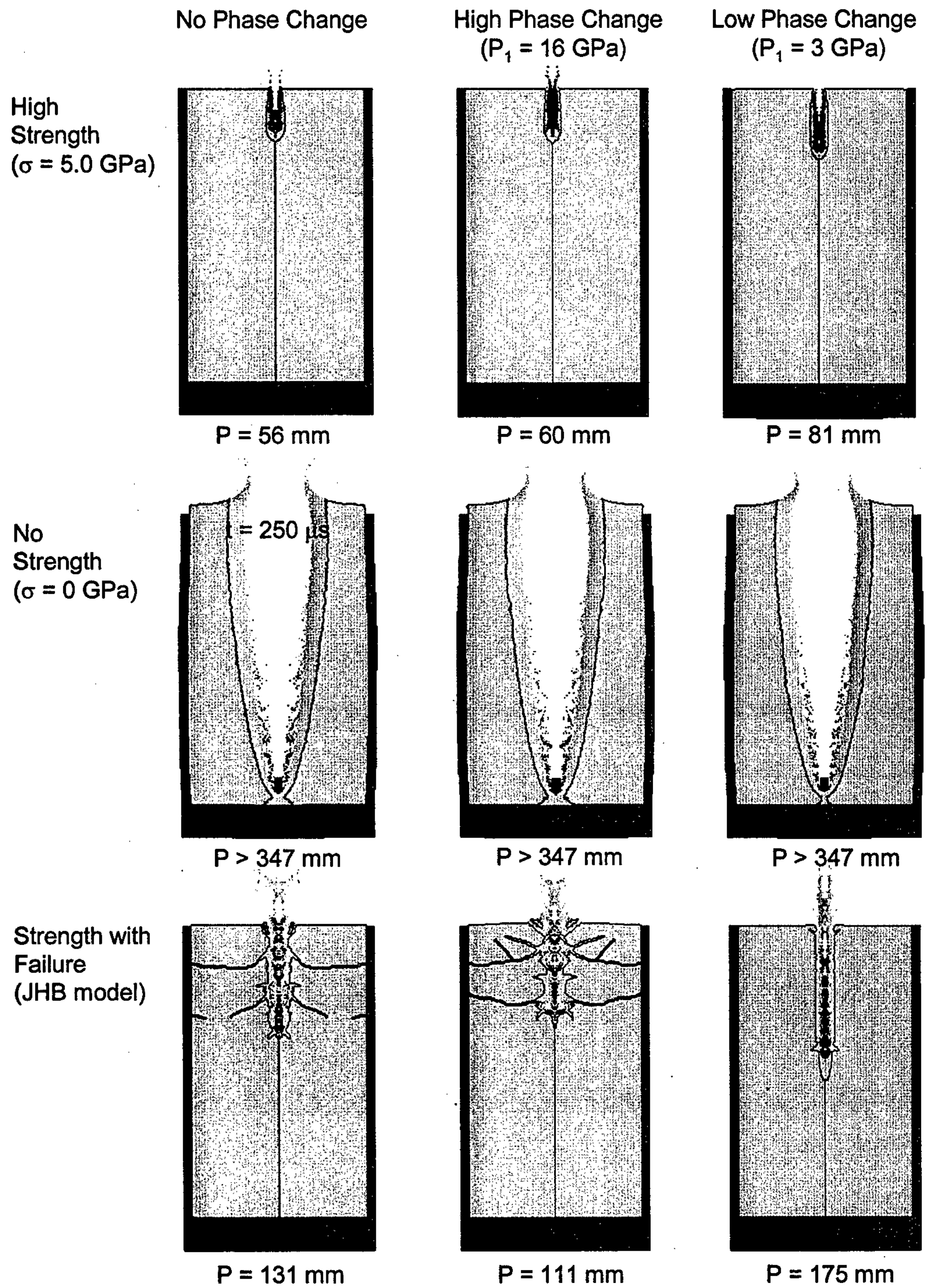

FIGURE 4. Computed results for the 2D projectile impact problems; for three phase change conditions (no phase change, high phase change and low phase change) and three levels of material strength (high strength, no strength and strength with failure).

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Effect of Hysteresis on Penetration

Figure 5 shows the effect of hysteresis. The low phase change condition and a constant material strength of 2 GPa are used. The low phase change ensures that much of the material will experience the phase change and the constant strength ensures that the phase change and strength are decoupled. The level of strength (2 GPa) was chosen because it represents about the average material strength for AlN and gives realistic penetration depths for a 2000 m/s impact velocity. Two variations in hysteresis behavior are investigated, no hysteresis and full hysteresis. No hysteresis occurs when the pressure-volume unloading path follows the same path as when loading. This results in little volume loss and little energy absorption (for the hydrostatic component). Full hysteresis occurs when the pressure-volume unloading occurs along a stiffer path, resulting in significant permanent volume loss and energy absorption. The maximum amount of permanent volume loss for this study is $\mu \sim 0.25$ as shown in Figure 1 (at $P = 0$).

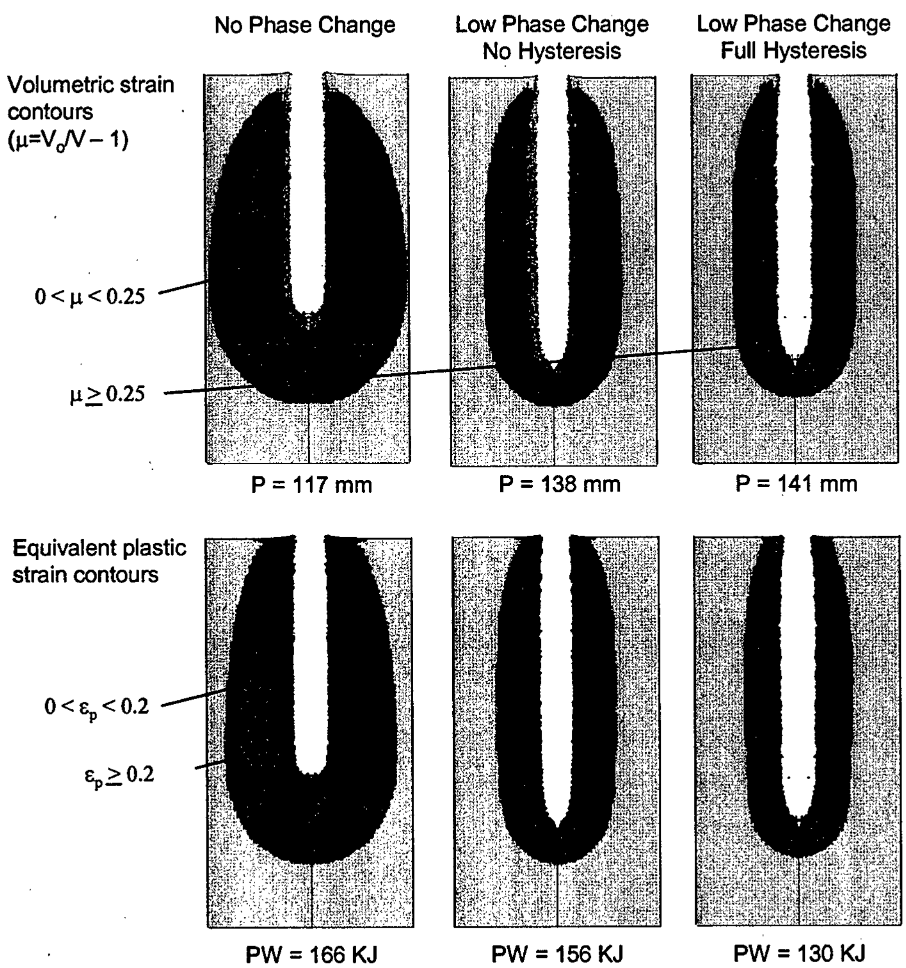

FIGURE 5. Computed results for the 2D projectile impact problems, for three phase change conditions. A constant material strength of 2 GPa is used for all three phase change conditions. Volumetric stain and plastic stain contours are shown for the target. The projectile is not shown. PW represents the total plastic work in the target.

Figure 5 presents the penetration results including volumetric and equivalent plastic strain contours. The results show that penetration increases by approximately 20% (independent of hysteresis) when a low phase change occurs. The increase in penetration results from the softer material response produced by the phase change. The effect of hysteresis is shown in the right two penetration channels in Figure 5. The effect is small when evaluated by penetration depth alone, but there is a substantial difference in how they absorb energy. The penetration channel with no hysteresis shows smaller volumetric strains and more equivalent plastic strain (and plastic work) than the channel with full hysteresis. When there is no hysteresis the material tends to unload and return to its original volume. This unloading process produces plastic strain (and plastic work). In contrast, when the material unloads with full hysteresis the material does not return to its original volume, but some lesser volume. This process creates less plastic work, because of the smaller unloading strains, but it also absorbs significant hydrostatic energy because of the permanent volume loss. In summary, the no hysteresis response produces more plastic strain and less volumetric strain and the full hysteresis response produces more volumetric strain and less plastic strain.

Effect of Phase Change, Strength, and Hysteresis on Shock Waves

The results of the plate impact computations are presented in Figure 6. The three phase change conditions are used for each of the three strength levels. The high and low phase changes are also computed with and without hysteresis. The top portion of Figure 6 shows the results using the high constant strength of 5 GPa. When no phase change occurs, a classic wave profile comprised of a faster moving elastic wave and a slower moving plastic wave is produced. The peak stress is approximately 47 GPa and the Hugoniot Elastic Limit (HEL) is 6 GPa. The results obtained using the high phase change are represented by the light grey line and show a three wave structure. The first wave is the fastest moving elastic wave, the second wave is produced from the HEL up to the phase change and is slightly slower, and the third wave occurs from the loading response from the phase change to the peak Hugoniot stress (approximately 34 GPa). There is only a slight difference in the unloading wave when there is no hysteresis. The low phase change response is represented by the heavy dark line and again is represented by a three wave structure. The primary difference here is the phase change occurs before the Hugoniot Elastic Limit and is why the first break in the wave (~ 5 GPa) is lower then the HEL (6 GPa). The HEL is reached very soon after the phase change occurs and continues to load to the peak Hugoniot stress of approximately 32 GPa. Because the HEL and low phase change occur at very similar levels the three wave structure is not as distinct as that produced by the high phase change. There is no difference in the wave profile whether hysteresis is used or not. The response is identical because upon unloading, the stress level never reaches the phase change stress.

The results of the plate impact computations, when no strength is used, are presented in the middle portion of Figure 6. When no phase change occurs the wave is a single structure and travels at the velocity determine by the slope of the stress-strain path from zero to the Hugoniot stress (~ 45 GPa). The high phase change produces a two wave structure which occurs due to the phase change at 16 GPa. The peak Hugoniot stress is approximately 32 GPa. The low phase change produces a two wave structure, similar to the high phase change response, but the wave transitions at a much lower stress (3 GPa) due to the low phase change. Because of the low phase

change pressure, the second wave travels faster than the second wave of the high phase change response.

The results of the plate impact computations, when strength with failure is used (JHB model), are presented in the lower portion of Figure 6. The responses are very similar to the responses produced from the high strength condition (upper portion of Figure 6). This occurs because the material does not fail under uniaxial strain conditions. The only difference between the high strength and strength with failure responses is due to the strain rate effect in the JHB model.

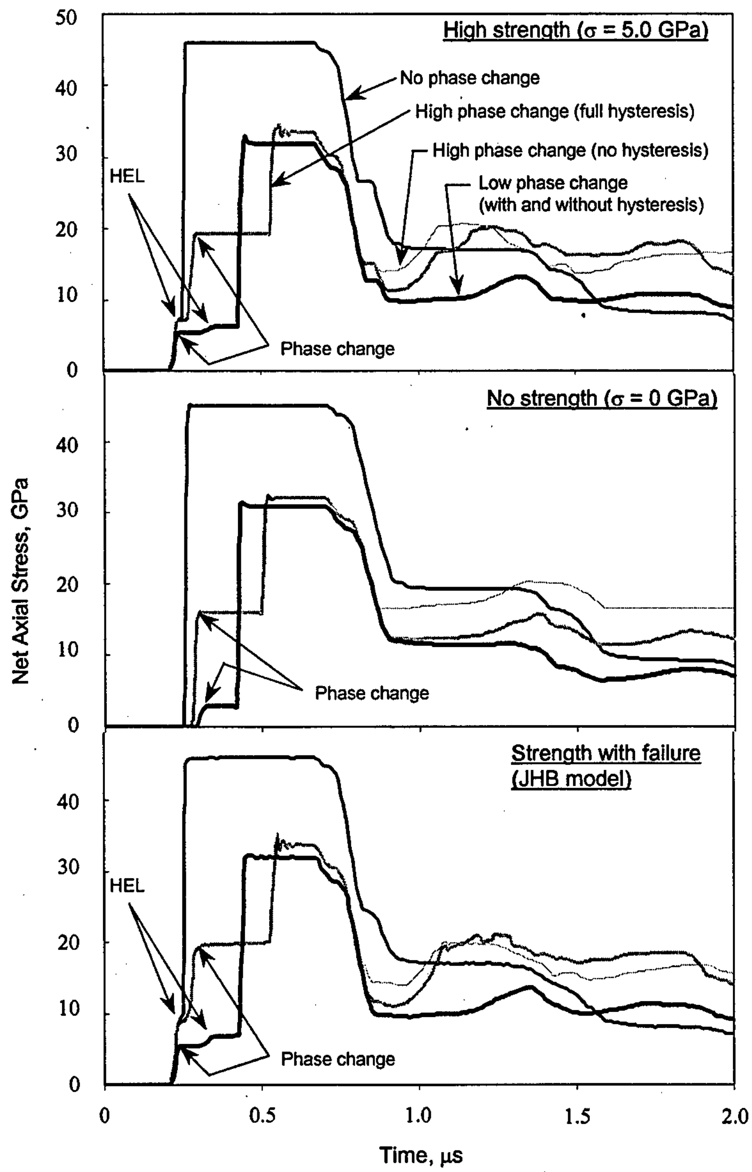

FIGURE 6. 1D plate impact results for three phase change conditions (no phase change, high phase change and low phase change) and three levels of material strength (high strength, no strength and strength with failure).

SUMMARY AND CONCLUSIONS

This paper has presented computed results that investigated the effect a material phase change, and strength, had on penetration and shock waves. Three phase change conditions and three levels of material strength were used. The results showed that penetration was very sensitive to the level of material strength and less sensitive to the phase change pressure. The shock wave response showed more sensitivity to the phase change condition and less sensitivity to the level of strength. More importantly, the results demonstrated that when a volume loss phase change occurs, it produces a softer material response, which reduces the material resistance.

The effectiveness of an armor material depends on many of its characteristics. It appears from this work that the presence of a volume loss phase change reduces the ballistic efficiency of the material.

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